

Prediction of PEMs & SMT Component Performance in Field Applications*

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Problem: How do we predict the reliability or failure probability of electronic components stored or deployed for extended periods of time?

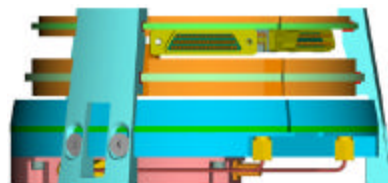
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How Do We Make Lifetime Predictions for an Electronic System?

- Very high reliability required for systems with an extended storage & deployment time, ~ 20 – 30 y.
- Reasonably large build numbers preclude extensive component screening.
- Lifetime environment includes: temperature, humidity, thermal cycle, shock,.....
- Relatively large extrapolations of accelerated test results are required for life prediction.

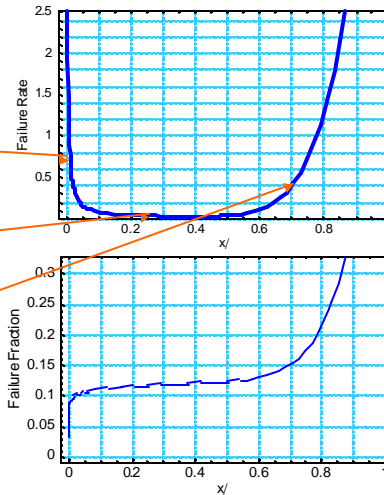


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Reliability of Electronic Systems – “Bathtub Curve”

- Electronic systems are characterized by three regions in the failure rate vs. time graph:

- **Infant mortality**
 - Failures due primarily to serious manufacturing defects.
- **Useful life**
 - Failures caused by defects or “early wear-out”.
- **Strong wear-out**
 - Failures caused by fundamental wear-out mechanism corrosion, fatigue,...



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Potential Electronics “Wear-out” Mechanisms

- What are some known wear-out mechanisms which might produce failure during the useful “life-time” of the part?
 - Plastic Encapsulated Microelectronics (PEMs)
 - Conductor corrosion in temperature & humidity (T&RH) aging.
 - Au-Al bond failure in temperature and/or humidity aging (HTS).
 - Die fracture or cracking from thermomechanical fatigue (TMF).
 - Radiation induced parametric degradation.
 - Surface Mount Technology (SMT)
 - Thermomechanical solder fatigue (TMF).
 - Vibration induced solder fatigue.
 - PWB corrosion.
- Wear-out failures + late defect failures ⇒ useful life failure rate.

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Problem – How Do We Predict Failure Rates From Available Data??

- Available failure mechanism models have many uncertainties:
 - Uncertainty in model parameters.
 - Uncertainty in applicability of a given model to a given component.
- The component or PWA environment is not well specified over the product lifetime.
 - Temperature
 - Humidity
 - Vibration
 - Chemicals
 - Shock
- Customer wants a prediction even with the above uncertainties.



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Example – Temperature & Humidity Aging of PEMs

- Peck “model” of temperature/humidity aging is widely used but:
 - Model parameters are very uncertain.
 - Component manufacturer accelerated T & RH test data are sparse & poorly defined.
- Variable environmental loads
 - Discrete events.
 - Cyclical events.
- Solution:
 - Treat model parameters as random variables, use Monte Carlo method to calculate a distribution of times to failure.
 - Use Miner’s rule to combine environmental load-events.



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Peck Model for Temperature & Humidity Aging of PEMs

- S. Peck, "Comp. Model for Humidity Testing Correlation", *Proc. 24th IRPS*, 1986:
 - Peck analyzed existing lifetime(T,RH) data for THB(85°C/85% RH) & HAST(>100°C) and derived an "acceleration factor" relation for the time to failure, t_f in HAST relative to THB.
- Peck model has been widely attacked but is has been and is still being used extensively:
 - Example: CALCE CADMP component failure analysis program uses Peck model in its PEMs corrosion module.

$$t_f \propto [RH]^{-n} \exp(E_a / k_B T)$$

$$n \approx 2.7$$

$$E_a = 0.79 \text{ eV}$$



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Some Reported Values of HAST/THB Peck Model Parameters

$$AF_V(V, V_0 | a, b) = \frac{a + bV}{a + bV_0}$$

$$AF_T(T, T_0 | E_a) = \exp \left[\frac{E_a}{k_B} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right]$$

$$AF_{RH}(RH, RH_0 | n) = \left(\frac{RH}{RH_0} \right)^n$$

Acceleration model parameters derived from experiment or literature data review by various authors

Sandia Report: D. R. Johnson et. al, "Microelectronics Plastic Molded Packaging", SAND97-0162, May 1997

Reference	Reported Mechanism	a	b	n	E _a (ev)
S. Peck, Ref. 24 th IRPS, 1986	Electrolytic corrosion	1	0	2.66	0.79
O. Hallberg & S. Peck, Qual & Rel. Engr, 1991	Corrosion	1	0	3	0.90
Lehigh RwoH Semi-Ann. Tech Rpt, 1992	Corrosion	1	0	1-5	0.88
G. Shirley, 32 nd IRPS, 1994	Passivation defect and transistor failure	0	1	4.64	0.79
G. Shirley, 45 th ECTC, 1995	Passivation defect and transistor failure	1	0.58	4.64	0.79
Shirley & Shell-DeGuzman, 3 rd IRPS, 1993	Au ball bond degradation on Al pad	1	0	1	1.1



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Miner's Law of Accumulated Damage

At constant environmental stress conditions denoted by s , a part is assumed to have a time to failure $t_f(s)$.

The damage to a component after time t at condition s is assumed to be proportional to $t / t_f(s)$.

A component will fail when the accumulated damage is unity:

$$\sum_i \frac{t_i}{t_f(s_i)} = 1$$



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Outline of PEMs T & RH Performance Prediction

- Develop a “life-time” $T(t)$ & $RH(t)$ profile:
 - Discrete events – Occur only one or a few times during lifetime.
 - Cyclic events – Occur regularly on a periodic basis.
- Determine the distribution functions for the model parameters:
 - Thermal activation energy, Q_a .
 - Humidity exponent n .
 - Parameters characterizing the failure distribution function at accelerated test conditions:
 - Time to 50% failure and std. deviation (t_{50} & σ)
- Perform a Monte Carlo analysis to calculate the time to failure t_f distribution function.
- Implement with commercial software.



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Examples of Inputs for the Events Tables

Annual Events

Interval	Event	T(°C)	RH(%)	Annual Fraction	D _t (h)	AF	AF·D _t	Accum. AF·D _t	Accum. Damage/year
1	Submarine deployment	28	30	0.4	3504	1.81E-05	6.34E-02	0.06335	0.00003
2	Storage facility	35	50	0.4	3504	1.69E-04	5.91E-01	0.65404	0.00029
3	Submarine maint.	33	75	0.1	876	4.67E-04	4.09E-01	1.06342	0.00047
4	Transport	45	85	0.05	438	2.13E-03	9.35E-01	1.99825	0.00088
5	Misc.	65	85	0.05	438	1.20E-02	5.25E+00	7.24621	0.00320

Discrete Events

Event No.	Event	T(°C)	RH(%)	No. Days	D _t (h)	AF	AF·D _t	Accum. AF·D _t	Accum. Damage
1	System test	30	50	10	240	1.03E-04	2.46E-02	0.02462	0.00001
2	System installation	25	75	5	120	2.07E-04	2.49E-02	0.04948	0.00002
3	Transfer to customer	28	85	6	144	4.11E-04	5.92E-02	0.10870	0.00005
4	System refurbishment	28	65	30	720	1.84E-04	1.32E-01	0.24111	0.00011

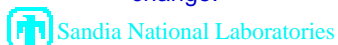
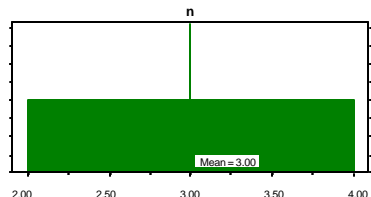
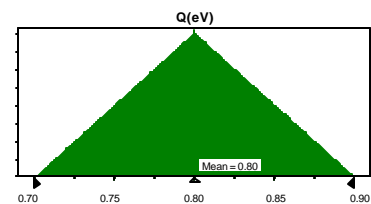
AF = "Deceleration Factor" relative to accelerated test conditions. It is calculated during the Monte Carlo evaluation.



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Distribution Functions for the Peck Parameters

- Activation energy Q_a is assumed to have a triangular distribution with a mean at 0.8 eV.
 - Not too interested in high Q_a because lifetime long there.
 - $Q_a = 0.6$ eV is about lowest value reported.
- RH exponent n is assumed to have a uniform distribution, $2 \leq n \leq 4$.
 - Possibly the range should be $1 \leq n \leq 4$. Easy to examine the consequences of this change.



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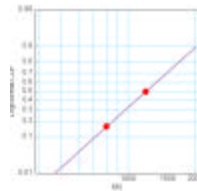
Distribution Function for Time to Failure at Accelerated Conditions

- Many experiments have shown that the time to failure distribution function is approximately lognormal.
- Parameters:
 - μ and σ .
 - Times to 16% and 50% failure, t_{16} and t_{50} .
- Major problem is that accelerated test data are usually not available or are not complete:
 - Usually ~ "0 failures in group of 75 parts after 100 h @ 130°C/85% RH."

$$CDF(t | t_{16}, t_{50}) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{\ln(t) - \ln(t_{50})}{\sqrt{2} \ln(t_{50}/t_{16})} \right) \right]$$

$$m = \ln(t_{50})$$

$$s = \ln(t_{50}/t_{16})$$



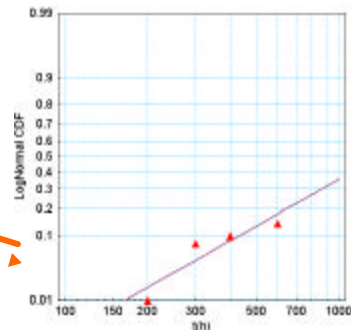
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Process for Assigning CDF Parameters

- If only manufacturer "no-fail" data:
 - Set $CDF(1.1 \times \text{test time}) = 1/(2 \times \text{no. parts tested})$
 - Set the standard deviation $\sigma = 0.5$, $\Rightarrow t_{50} = 1.7 t_{16}$.
- If manufacturer has "failure" data:
 - Set the CDF value at the observed failure fraction.
- If additional data are available, set the CDF t_{16} and t_{50} at "least squares" derived values.

$$m = \ln(t_{50})$$

$$s = \ln(t_{50}/t_{16})$$



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Implementation

- The program is implemented in MS Excel with the Crystal Ball Monte Carlo *add-in*.*
- Crystal Ball allows one or more cells to be “assumption” cells or random variables described by distribution functions.
- Can set one or more cells as “forecast” cells for which a distribution of values is obtained.
- We typically run ~ 10000 calculations \Rightarrow ~ 30 s on an 800 MHz computer.

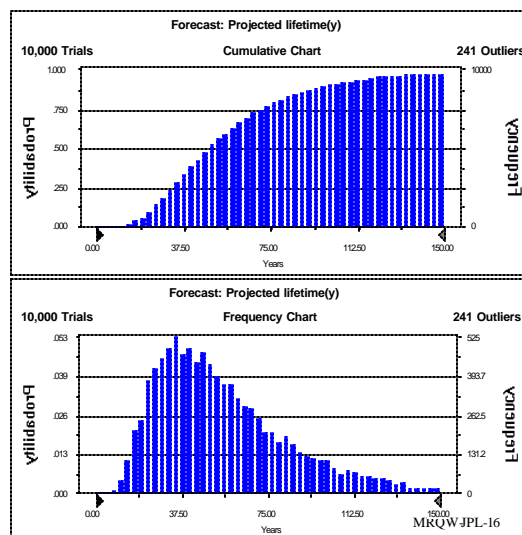
* Reference to a commercial product implies neither an endorsement by Sandia National Laboratories nor a lack of suitable substitutes.



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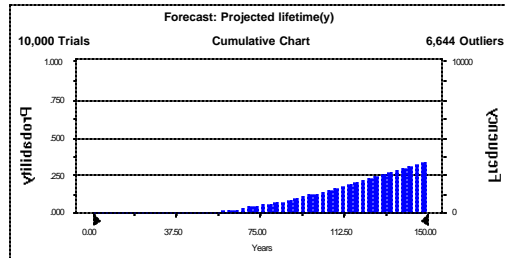
Example – Only “100 h 130°C/85% RH No Fail Data” for 100 Parts

- Forecasts show CDF & PDF for projected lifetime.
- For the input environmental conditions, the lifetime does not appear to be adequate.
- Potential resolutions:
 - Obtain longer time HAST data.
 - Refine the conditions.



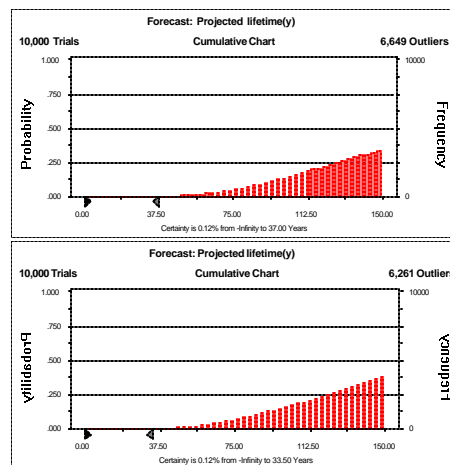
Effect of Having “No-Fail” HAST Date for 350 h.

- Assume that no fail HAST data are available for 350 h at 130°C/85% RH.
- In this case, the Monte Carlo calculation shows that there should be a 30 y lifetime at the input T & RH conditions.
- This result seems fairly general, 100 h HAST data are not sufficient for our application.



Effect of Changing the RH Power Law Distribution Function

- Top graph $2 \leq n \leq 4$
 - Based on available “data”
- Bottom graph $1 \leq n \leq 4$
 - Based on Leheigh RwoH work. Results in shorter t_f .
- Result:
 - 0.12% failure probability point moved from 37 → 33 y.
 - Demonstrates relative insensitivity to exact lower cutoff of the n exponent CDF.



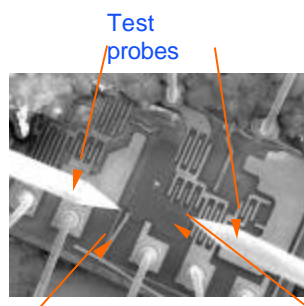
New PEMs Component Insertion

- PEMs GaAs devices are becoming widely available for rf applications: cell phones, radars, μ wave links,.....
- There is little or no information available about the failure mechanisms & associated reliability of these parts.
- Typically, GaAs devices use Au metal and frequently no passivation layer. Often, a polyimide die coat is used for PEMs.
- There is no a-priori reason to assume that the Peck parameters will apply to a GaAs PEMs device.
- Example: Alpha Industries AS186-302 High Isolation SPDT switch, 0.5 – 3.0 GHz.
 - Reported: 0 failures out of 45 parts in THB(85°C/85% RH), 1000h.



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AS186 rf Switch



Plated Au top metal
delamination after
1000 hours
HAST(130°C/85% RH

New failure mechanism -Au metal
"delamination". Not seen in TC

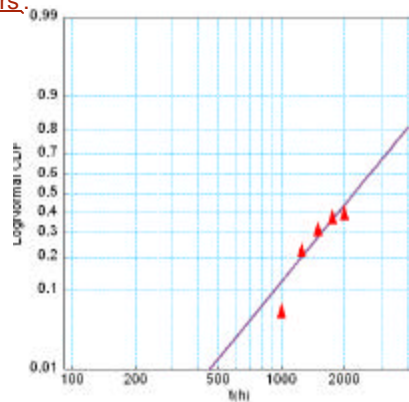
Fit Parameters:

$t_{50} = 2222$ h

$t_{16} = 1123$ h

$\mu = 7.7$

$\sigma = 0.68$



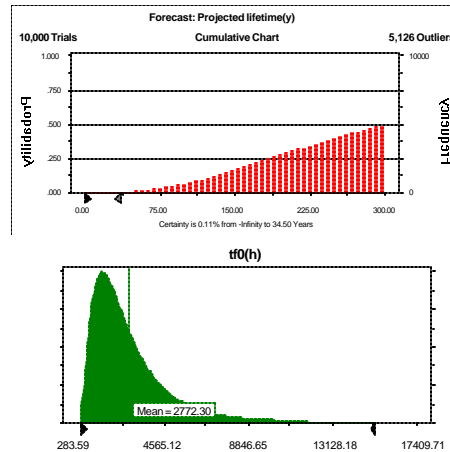
130°C/85% RH HAST – SNL Data



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Forecast of AS186 Failure Distribution Function

- Forecast failure points:
 - 0.01% - 19 y
 - 0.1% - 34 y
 - 1% - 57 y
- Largest contributor to the wearout:
 - “Miscellaneous” exposure to 65°C/85% RH for 5% of a yearly cycle, ~ 4X the “Transport” contribution.
- Suggests that better definition of the “Miscellaneous” environment will lead to a longer life prediction.



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Surface Mount Technology Solder Fatigue

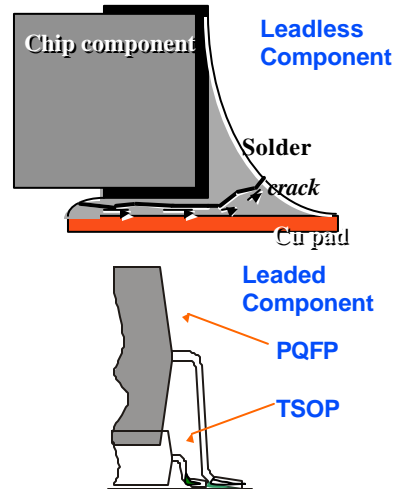
- Thermo-Mechanical Fatigue (TMF) of solder joints can produce cracks and eventual failure by complete opening.
- The mechanism is difficult to analyze because of:
 - Uncertainties or variations in the solder constitutive relations: creep, plastic deformation.
 - Uncertainties in material properties and geometric parameters.
 - Long calculation time for “accurate” Finite Element Models (FEM).
 - Uncertainty in relating calculated quantities(maximum inelastic strain,...) to *cycles to failure*.
- For a long life application it is important to perform a TMF analysis on all SMT components on a PWA.



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Solder Fatigue & Crack Growth

- Thermo-Mechanical solder Fatigue (TMF)
 - Occurs during thermal cycling & mechanical vibration.
 - Results from crack initiation & growth due to grain coarsening & slip.
- Process & rate of TMF affected by many variables:
 - Component – lead type
 - PWB
 - Surface mount assembly
 - Environment



General Approach - a “Work in Progress”

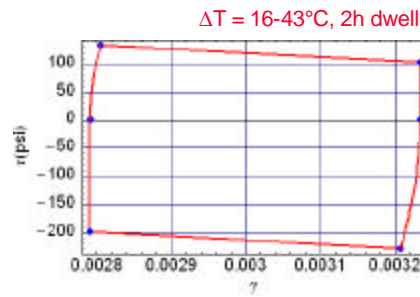
- 1st - require a model which is reasonably accurate and runs quickly:
 - Solder Reliability Solutions (SRS) commercial TMF calculator – Jean-Paul Clech:
 - Calculates “average” solder strain using analytical expressions.
 - For a step function $\Delta T(t)$ drive function it executes very rapidly.
 - Documented extensively in the literature & “validated” at SNL.
 - Extensive correlation with fatigue data used to derive the relation between cycles to failure and stress-strain hysteresis loop area.
- 2nd – Define the major “random” variables in the problem:
 - Solder paste area & thickness.
 - Coefficients of expansion of the constituents.
 - Solder creep law parameters.

SRS Validation – SOT23 PEMs Part

Comparison between SRS global mismatch hysteresis loop and SNL/Mathematica calculation of the same quantity.



SRS output of hysteresis loop



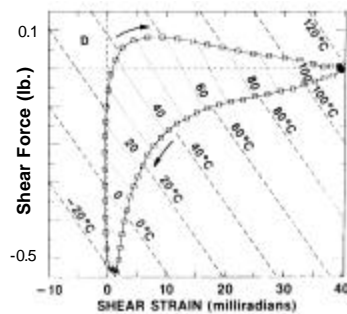
SNL loop calculation, lead stiffness from SRS



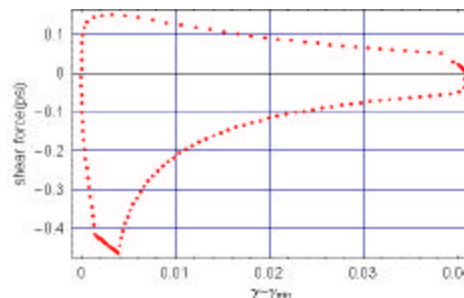
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Extension of SRS to Arbitrary Thermal Variation

Validation of the modified SRS model against Peter Hall's data on LCCC thermal cycling, as obtained with strain gage instrumentation.



P. Hall experimental data



SNL/modified SRS calculation



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Future Work on the Modified SRS/Monte Carlo Solder Fatigue Model

- Implement the modified SRS model in Excel:
 - Translate Mathematica code to Visual Basic.
 - Startup problems for low lead stiffness.
- Develop a Monte Carlo analysis with Crystal Ball
- Examine the potential change of the loop area – cycles to failure empirical correlation:

$$\frac{N_f}{A_{\text{solder}}} = \text{const.} (\Delta W)^{-n}$$

- Correlate results with SNL FEM & solder grain growth analyses.